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Sustainable Manufacturing Process in the Context of Wood Processing by Sanding

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Abstract: The aim of this paper is the issue of a sustainable manufacturing process in the context of woodworking by sanding, as one of the most important technological operations before its final treatment, focusing on a selected pillar of sustainable manufacturing process, waste management. The first step of the experiment was to optimize the pressures of the sanding means on the surface. The optimal pressure of 1.04 $N \cdot cm^{-2}$ was chosen. The second level was to obtain the wear curves of the abrasive means with grain size 80 (evaluated by wood removal) and the optimal pressure in dependence on the sanding direction (along and perpendicular to the wood fibres and in the direction of 60° to the wood fibres) and different types of woods (beech, oak, alder, pine). The set parameters were suitable for beech and were not suitable for alder and pine. By extending the operating life of the sanding belts via appropriate choice of input factor settings it can be influenced metrics of pillar waste management-savings of material and waste minimization.

Keywords: sustainable manufacturing process; wood sanding; various input factor; wear of sanding means

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1. Introduction

The wood sanding process is one of the technologies that significantly affects the resulting quality of the wood surface, to which the quality of the product itself is related. In particular, the sanding of wood and wood materials is aimed at achieving pre-sanding (smoothing out roughness of functional surfaces of the workpiece), calibration (achieving the same workpiece thickness), fine sanding (surface preparation before the application of paints, increasing the adhesion of the coating), smoothing (polishing of the varnished surface), or improving the aesthetic look of the treated surface [1–3]. In terms of the final effect, it is a technology that will also affect the number of coatings applied, the operational life of the surface film, etc., as sanding is the last processing operation before the surface-finishing treatment.

Sanding, as a technology, is also interesting from the viewpoint of the tool used, which is not sharpened and thus, after wearing (blunting), must be replaced. Thus, a large amount of the abrasives themselves is consumed and, therefore, sanding is classified as a time-consuming and costly operation [2,4–11].

The wood-sanding process, also according to this brief description, is very complicated and needs to be examined from different points of view, one of them being the sustainability of the manufacturing process. In our production facilities, due attention is not paid to the issue of a sustainable manufacturing process and the upper management of the companies does not often consider its solution as urgent because, in society, the view remains that it is an issue that primarily affects the environment [12,13]. Of course, the concept of sustainable development or sustainability is a notion that was defined in the 1970s in relation to environmental issues. In 1992, the UN Conference on Environment and Development (called the Earth Summit) brought a new approach to the problem of sustainable development, which focuses more comprehensively on sustainability issues, not just in terms of environmental but also economic and social issues. However, only in 2015, the UN developed, within the 2030 Agenda, the "Transformation of our world" programme: Sustainable Development Agenda 2030, which includes the first and separate objective No. 12: "Sustainable consumption and production". "Sustainable production" is identified and analysed at three main levels, namely, at the level of products, processes, and systems. The interaction between these levels provides the objective of sustainability [14,15].

2. Theoretical Analysis

This contribution deals with a sustainable manufacturing process that is based on six pillars (manufacturing cost, energy consumption, waste management, operational safety, personal health, environmental impact), with measurable results that must be examined at all inputs and all outputs of the manufacturing process to achieve a sustainability objective [16].

In the machining process, we proceeded according to the scheme [17], where, through the examination of all inputs and outputs, the resulting product quality and the minimum consumption of energy and other input materials, with a minimal impact on the working and outside environment, it was possible to optimize a specific machining process and thus meet sustainability targets. This examination is necessary to perform for all machinery throughout the production cycle.

The aim of the presented contribution is to evaluate the process of wood machining by sanding in terms of sustainable manufacturing processes (i.e., by recapitulating the experimental results obtained so far) and how the choice of selected parameters at the input level within the wood sanding process with the hand-belt sanding machine will affect the output in terms of tool wear, i.e., a pillar of a sustainable manufacturing process—waste management—where the measurable outputs include, e.g., waste minimization, saving materials, reusing waste materials, the amount of consumables replaced, etc.

In the presented contribution, not all input and output factors are analysed, but only those (Figure 1) which were and are the subject of our long-term research interest. However, as an example, they are sufficient to point out the high importance of such an analysis (in production operations themselves) because they significantly affect sustainability pillars and their specific measurable outputs.

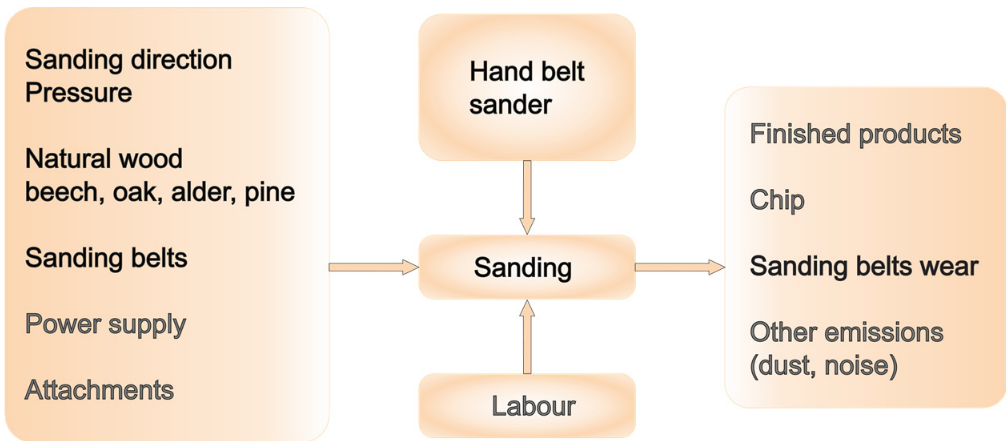

Figure 1. Example of the machining process from the perspective of sustainable manufacturing.

2.1. *Brief Characteristics of Factors on Input*

2.1.1. Processing Parameters—Sanding Direction

The structure of the wood and the anisotropy of its properties also affect the way that fibres are cut. According to [1], sanding the wood in a direction perpendicular to the fibres removes the roughness of the surface intensively. The wood fibres on the surface are broken and divided to countless short fibres, and there is a problem when removing them from the sanding surface with such a direction of sanding. When the sanding is done only in the longitudinal direction, the sanding is not so intensive; the long chips of the fibrous shape are produced, twisting between the sanding belt and the wood, which subsequently prevents the intense touch of the belt with a sanded surface. Such chips also very easily clog the sanding means. When sanding in the longitudinal direction, the separation of fibrous wood surface elements is not perfect; they are partially removed and partially pressed into cell cavities. As the so-called "cross-sanding" is used in practice, hence alternating the sanding along the fibres and perpendicular to the fibres, one of the factors of the research performed was also this parameter [2].

2.1.2. Processing Parameters—The Pressure of the Sanding Means to the Surface of the Workpiece

In order to obtain the expected parameters of the workpiece surface before coating, it is important to obtain a smooth surface that is achieved by using a high-quality sanding means with a corresponding granularity as well as the pressure of the sanding tool to the surface of the workpiece. If the pressure is insufficient when sanding hardwood, the sanding belt may not take any chips, and if the pressure is too high, it will cause a high load on the sanding belt, causing it to degrade rapidly and it must, therefore, be replaced [10,18–20]. When softwood is sanded under high pressure, a large amount of chips will form immediately from the start of the sanding tool, which quickly fill the space between the grains and clog their spikes, and the sanding tools gradually lose cutting efficiency [21].

2.1.3. Raw (Machined) Material—Natural Wood (Beech, Oak, Alder, Pine)

When sanding wood, it is necessary to consider the different physical-mechanical properties of wood, which depend on its structure, density, the width of its growth rings, the proportion of summer wood with a significantly higher density than spring wood, especially in coniferous trees, its moisture, resin content, etc., and the anisotropy of these properties in wood volume depend on direction [22–24].

In terms of sanding, soft woods are sanded significantly worse than hardwood, and therefore, with the same factors, the smoothness of the hardwood surface is higher than the softwood surface (springing of the material and cut fibres). Resin, which is part of some coniferous woods, plays a negative role in the sanding process because, along with sanding dust and chips, it rapidly clogs the sanding belt, compared to wood that does not contain resin [3,25]. Moisture from wood reduces the efficiency of sanding, that is, the amount of material removed per unit of time from a particular surface [26].

2.1.4. Cutting Tools—Sanding Belts

The sanding means is the agglomerate of many small, individually allocated wedges of various irregular shapes, called sanding grains, which carve macro-particles from the wood—a wooden dust. The cutting wedges of the sanding tool are mostly of negative rake angles that cannot be sharpened, and after blunting, the sanding means must be taken out of operation. The basic characteristics of the sanding means are the underlying material, bonding material, type of abrasive, graininess (the size of the base fraction of the sanding grains), type of spreading (mechanical or in an electrostatic field)—open, semi-opened, or dense—antistatic treatment, and proper storage of the sanding means. The quality of the sanding means is characterized by the maximum total wood removal and working time while maintaining the economy of sanding—the quality of the surface obtained [2,10,24,26,27].

2.2. *Characteristics of the Output Factors*

Used Cutting Tools—Sanding Belts Wear

The wear (dulling) of the sanding means is specific because it is not a classic tool with a precisely defined angular geometry, where the cutting wedge can be sharpened after the cutting edges are dulled. This mechanism does not apply to sanding; instead, the dulling of the tool or self-sharpening is applied. The dulling occurs due to the breaking of inappropriately oriented grains, rounding, and clogging with deformed chips particles, so that the sanding tool gradually loses its cutting efficiency. Self-sharpening occurs due to the breaking of parts of the grain or whole grains from the bonding material. After disintegration of the grain from the bonding material or breaking of the grain portion, new grains start to work, so the working surface of the tool is constantly renewed, which represents a specific property of the sanding tools. This process ends when the pressure force that is already operating on a grain is not sufficient for further breaches of the grains, and the grain is smoothed and loses resistance. The cutting process then changes to friction sliding between the tool and the workpiece, and the operational life of the sanding means ends and must be removed from the operation [28].

With sanding means, where the wear values of individual sanding grain surfaces are virtually immeasurable, the decrease in the amount of wood removal over time is used for a description of the wear of the sanding means (sanding efficiency). This dependence is called the wear curve of the sanding means and has three characteristic phases—initial sharpness, work sharpness, and dulling of the sanding belt [2,4,9].

The efficiency of the sanding means is most often expressed by the amount of wood removal in grams per minute from an area of 1 cm^2 of wood ($g{\cdot}cm^{-2}{\cdot}min^{-1}$)—specifically, wood removal.

The sanding performance is influenced mainly by the shape of the sanding means (belt, roller, disc), its grain size, hardness, the type of abrasive, the type of wood, the force of the pressure of the sanding means on the wood, and the direction of the fibres to the cutting speed vector [2,10,29–32].

With classic tools, the time for which the tool works until its wear (dulling) is called the operational life of the tool. A dulled tool may be sharpened. The sum of the tool's operational life until its full decommissioning is called the tool life.

With a sanding tool that cannot be re-sharpened, the operational life and tool life can be matched. The operational life of the sanding means, according to [33], can be defined as the time until the wood removal value is reduced to $\leq 0.05\ g{\cdot}cm^{-2}{\cdot}min^{-1}$. The tool life is the time for which the sanding means is able to sand off the maximum amount of wood material in grams or kilograms while maintaining the economy of machining (given by the value of the wood removal).

3. Materials and Methods

We will only briefly introduce the methodology of individual experiments with reference to the literature, with an accurate description [2,9,27,34].

3.1. *Machined Material—Experimental Samples*

For the experiments, samples were prepared according to Figure 2.

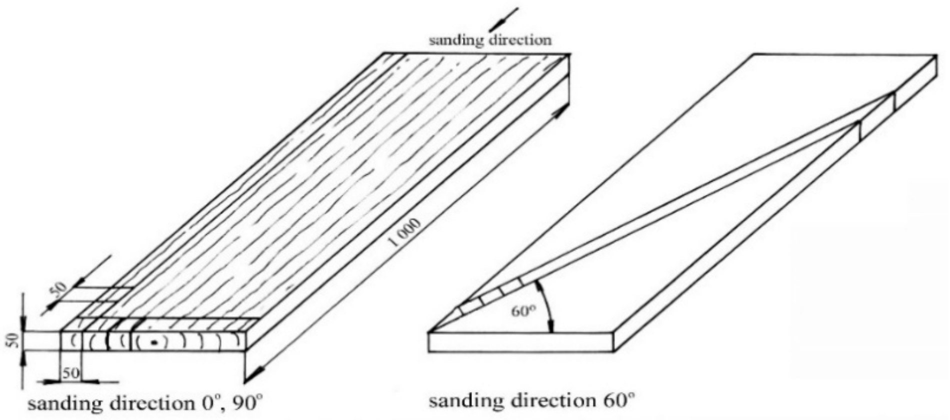

Figure 2. Preparation of samples.

The samples were cut to dimensions of 50 × 50 × 50 mm^3, so that the vector of the cutting speed and the direction of the wood fibres had an angle of 0°, 60°, or 90°. Before sanding, the samples were conditioned to a moisture content of 12%. Sufficient samples have been prepared for each variant, and also for each wood type. Approximately 150 samples were prepared for each type of wood, sanding direction, and for each of the 3 cycles. The samples were divided into 2 groups: test (control) samples without visible defects (about 30 pieces) and other samples (120 pieces). The samples for the experiments were selected according to the different physical-mechanical properties of the wood, as well as the economically exploited woods:

Red beech (*Fagus sylvatica*)—deciduous wood with scattered pores, hard, of moderate weight, with a density of 684 $kg \cdot m^{-3}$; European alder (*Alnus glutinosa*)—scattered deciduous porous wood, light and soft with a density of 528 $kg \cdot m^{-3}$; Common oak (*Quercus robur*)—deciduous wood with rings, hard and heavy with a density of 744 $kg \cdot m^{-3}$; European red pine (*Pinus sylvestris*)—coniferous wood containing resin. This wood is light, with a density of 550 $kg \cdot m^{-3}$.

3.2. The Pressure of Sanding Means to the Surface of Workpiece

Pressures selected for the experiments: 0.66, 1.04, 1.47, and 1.86 $N \cdot cm^{-2}$.

3.3. Tools

Klingspor LS 309 XH (KLINGSPOR, Haiger, Germany) endless sanding belts were used for the experiment, with the following input characteristics: sanding belt size—100 × 610 mm^2; grain size—80; abrasives—artificial corundum (aluminium oxide); bonding material—artificial resin; underlying material—cotton fabric, heavy; spreading—dense. For each variant of sanding, sharp sanding belts were used.

Before being used in the tests, the sanding belts were always conditioned at 20 °C and 65% relative humidity; 24 h before the experiment began, the test belts were stored in the room where the experiment was to be carried out.

3.4. Equipment

Experimental equipment: Stand for wood sanding—Bosch GBS 100 AE hand belt sander (Robert Bosch GmbH, Gerlingen, Germany), cutting speed 7.8 $m \cdot s^{-1}$, designed for monitoring of contact phenomena [35].

3.5. Measurement of Wear for the Sanding Means

For the experiments, samples of each wood were assigned to 2 groups. Testing samples have about the same number of growth rings in the frontal cut, and approximately the same weight contained a minimum of visible wood defects. The second group consisted of all other samples that were sanded between the test samples. All samples were weighed using Radwag WPS 510/C/2 digital laboratory balances (Radwag Balances and Scales, Radom, Poland) with a precision of 0.001 g, and dimensions of the test samples were measured with a digital caliper (Lutron, Coopersburg, PA, USA), model DC-515. The samples prepared in this way were prepared for the chosen sanding directions—0°, 60°, or 90°, and for the chosen woods. The sanding time was set for 480 min (approximately 1 work shift). The grain size of the sanding belts was 80. The measurements of the efficiency of the sanding means (wear) were made every 20 min, with 3 control samples that were sanded for 1 min (more sets were prepared). The weight of the samples before and after sanding was recalculated for a specific wood removal. These averaged values were the basis for determining the wear of the sanding means.

Between the testing measurements, other samples (3–4 pieces) were sanded, which were weighed at the beginning of sanding and after the sanding to a minimum value (clamping of the fixture). These values were the basis for determining the overall amount of material wood removal, that is, the operational lifetime of the sanding means [2,27].

4. Results and Discussion

4.1. Adjust the Uniform Pressure

On the basis of much research, it is known that the efficiency of the sanding means (the amount of wood removal) is substantially affected by the pressure of the sanding means applied to the workpiece surface. On the basis of the experiments that were carried out, these results can be confirmed. However, in order to compare the results of sanding belt wear for all selected woods and sanding directions, a suitable uniform pressure needs to be found. To adjust the uniform pressure, the so-called “easily” sanded wood, with scattered pores of beech, and the so-called ”heavy” sanded wood, with ringed pores of oak, were chosen. The results are shown in Figure 3 [27]. The matrix of the experiment is uneven in terms of paired pressure values for both sanded woods due to the fact that, during oak sanding, the sanding belt was broken at a pressure of 1.86 N·cm^{-2}, and therefore, the matrix was supplemented with a pressure value of 0.66 N·cm^{-2} for oak.

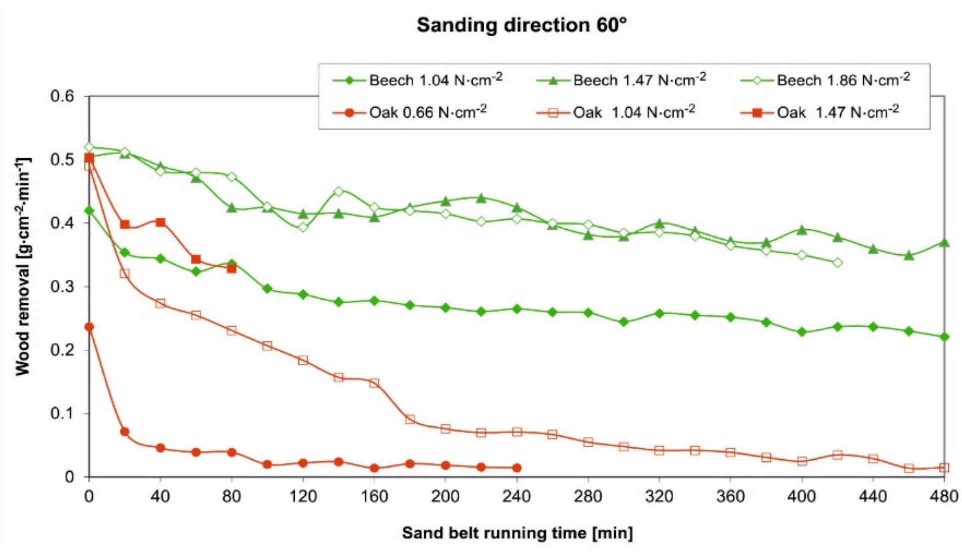

Figure 3. Optimization of the pressure for beech and oak.

For beech, the wear curves were obtained at a monitored time of 480 min for pressure values of 1.04 and 1.47 N·cm^{-2}. For a pressure value of 1.86 N·cm^{-2}, the wear curve was obtained for a period of 420 min.

In terms of specific wood removal, the pressure values of 1.47 N·cm^{-2} and 1.86 N·cm^{-2} are approximately the same, while at a pressure of 1.04 N·cm^{-2}, the value of wood removal is lower.

Since the pressure of 1.86 N·cm^{-2} did not significantly affect the efficiency of the sanding means (the amount of wood removal), it is excessively high, and also the working time of the sanding means is shorter, as the belt has been disrupted, which is the result of an already-unacceptable load on the sanding means [18–20]. These results can be confirmed by other research [21], (influence of the sanding means' pressure impact on the cutting force per unit of the cut surface) where, for most wood, the value of the cutting force increases with a growing pressure of the sanding means on the surface of the workpiece.

When sanding beech, even the lowest pressure of 1.04 N·cm^{-2} was not suitable because the quality of the sanding means was given by the maximum wood removal, and in the given case, the wood removal reached lower values than at the pressure of 1.47 N·cm^{-2}. Thus, the sanding belt capacity was not utilized sufficiently. From the point of view of the sanded surface, the thickness needed with the selected pressure of 1.04 N·cm^{-2} has not been removed and the workpiece should be subjected to repeated sanding (energy costs and time are increased).

In conclusion, it can be stated that when sanding beech wood, the pressure of 1.47 N·cm^{-2} is more suitable, whether from the point of view of efficiency or work time, but the interesting finding is that the minimum wood removal value of $\leq$0.05 g·cm^{-2}·min^{-1} was not reached with any pressure (which signals already-sufficient wear, or the dulling of the sanding means) [33]. At a pressure of 1.04, as well as 1.47 N·cm^{-2}, sanding belts are able to continue to work for a longer time than the set-up time of 480 min [27].

For oak wood, after repeated attempts, the pressure of 1.47 N·cm^{-2} was shown to be too high, and the sanding belts were disrupted after a relatively short work time of about 80 min. However, their efficiency at the beginning of the sanding was similar to that of the beech wood, within the sharpness of the initial phase.

At a pressure of 1.04 N·cm^{-2}, the wear curve of the sanding means was obtained throughout the monitored interval, but its efficiency gradually decreased to $\leq$0.05 g·cm^{-2}·min^{-1}, with an operating time of ca. 280–300 min, which, according to [33], reflects the time when the operational life of the sanding means ends or the sanding is not economical. To obtain a higher efficiency of the sanding means and extend their durability or operational life, the pressure of 0.66 N·cm^{-2} was chosen, but after the first 40 min of the sanding means' work, the value of wood removal dropped to $\leq$0.05 g·cm^{-2}·min^{-1}; i.e., the sanding belt did not remove any or minimal chips, friction between the sanding and the surface of the workpiece appeared, and the belt was interrupted after 240 min. These results are confirmed by [10,18–20]. According to [10], there was no consistent and predictable relation between the MRR (material removal rate) and the pressure.

When confronting these long-term experiments results with, the results of [21] for the short-term experiments, where, for oak wood, it was also suitable to have a pressure of 1.86 N·cm^{-2} or even 2.06 N·cm^{-2}, it is necessary to emphasize the need for long-term experiments, because short-term experiments (typical also for practice in order to obtain indicative values) do not always provide unambiguous information about the suitability of setting the input parameters.

Based on the experiments that were carried out, a pressure of 1.04 N·cm^{-2} was chosen to obtain the wear curves of the selected wood and the mutual comparison of their efficiency (Figures 4–6) [34]. The design of the experiment was based on the scheme in Figure 1. For the designed experiment, we took into account the following boundary conditions:

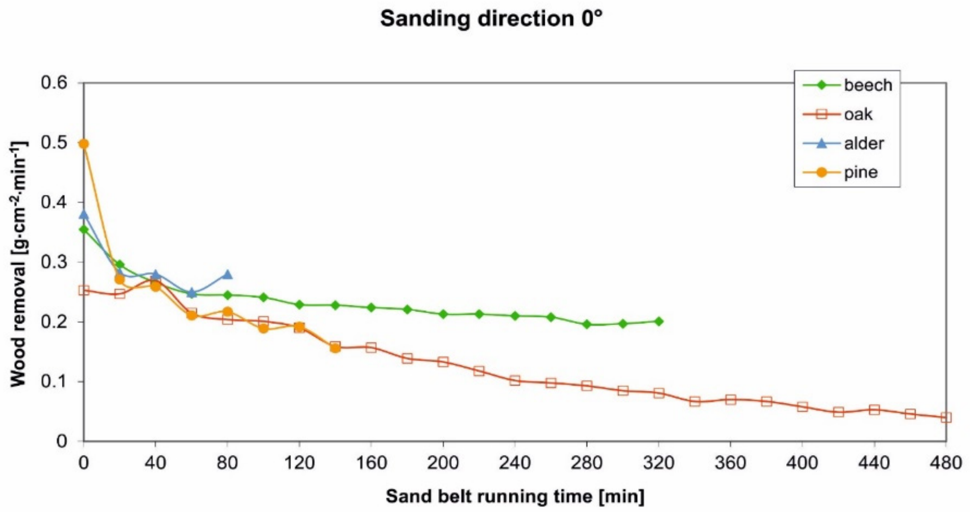

Figure 4. Wear curves for the sanding direction along the wood fibres at 0°—wood removal depended on the sand belt running time.

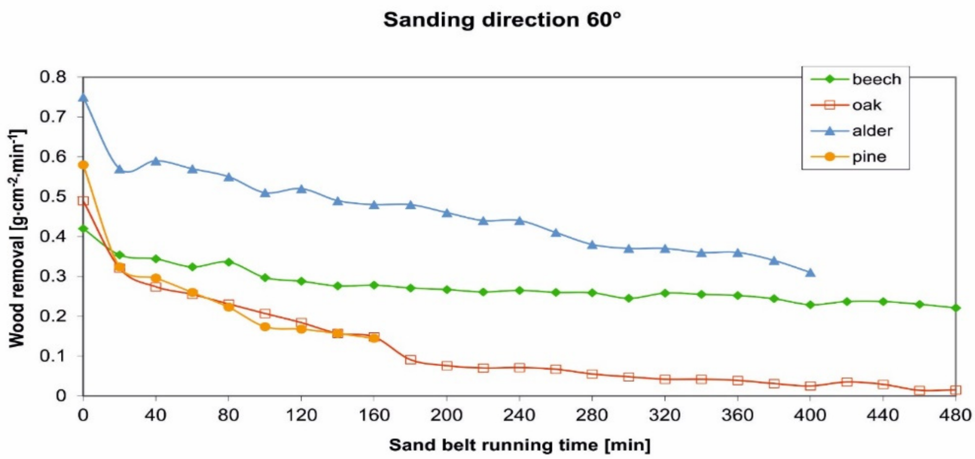

Figure 5. The wear curves for the sanding direction of 60° to the wood fibres—wood removal depended on the sand belt running time.

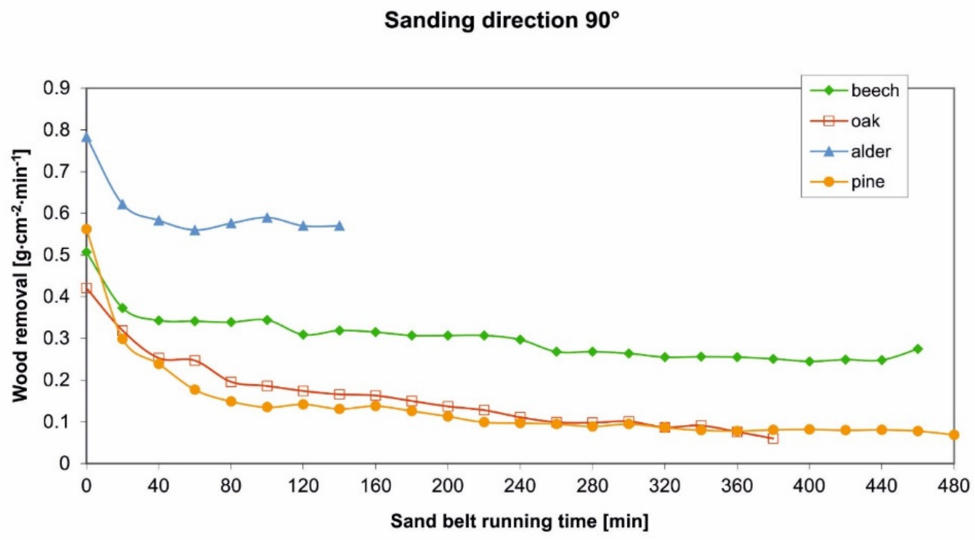

Figure 6. The wear curves for the sanding direction perpendicular to wood fibres—wood removal depended on the sand belt running time.

Process parameters:

Tool—a sanding belt with a grain size of 80; basic grain for the first stage of sanding; dense spreading;

Cutting speed—7.8 m·s^{-1}; the average value of possible settings was given by the manufacturer;

Pressure force—1.04 N·cm^{-2}; final value was based on input experiments to set a uniform pressure.

Material parameters:

Sanded wood—beech, oak, alder, and pine, which are types of economically exploited wood in Slovakia;

Humidity—±12% of the usual humidity of construction joinery products;

Cutting models—0°, 60°, or 90°, with respect to the coverage of cutting models during sanding.

4.2. Sanding Direction along the Wood Fibres

The wood removal values are different for the chosen woods, but in particular, the time of work for the sanding means varies. For all wood (excluding oak), the course of wear is marked by a large decrease in wood removal in the first 20 min, or the initial sharpness phase. In the sharpness phase of the work, the wood removal values for all types of wood are comparable. Soft and lightweight wood (alder, pine), when sanding along the fibres, produces a lot of chips, long chips that quickly fill the inter-chip space and the load on the sanding means increases. Therefore, they are disrupted rapidly—for the alder after 80 min, and for the pine after 120 min—and the presence of resin is also a negative factor [4]. The increased material removal rate inevitably resulted in an increase in temperature. This could overload the sanding belt and reduce its useful time, consequently breaking it [18,20].

For beech wood, the value of wood removal is balanced until the replacement of the sanding means at work (i.e., when they break), which is 320 min. Since the value of wood removal has not fallen below ≤0.05 g·cm^{-2}·min^{-1}, it can be concluded that even when sanding the easy-to-sand beech wood in a longitudinal direction, the conditions of the work of the sanding means are difficult.

With oak, we can see the lower wood removal values compared to beech wood, with a continuous decrease in the amount of wood removal until the end of the monitored interval of 480 min from 0.25 g·cm^{-2}·min^{-1}, up to the value of ≤0.05 g·cm^{-2}·min^{-1}. Sanding at the end of the test interval (after 400 min) is not effective and the sanding belt should be exchanged.

4.3. Sanding in 60° Direction to the Wood Fibres

Based on the obtained results, we assume that the machining conditions with this direction of sanding, whether the fibres are pruned, and the deposits and removals of the dust from the inter-chip space are less demanding for all selected woods in comparison to sanding along the fibres, which has been reflected mainly in the extension of the working time of the sanding means and also by higher wood removal values. Deciduous wood with scattered pores (beech, alder) achieves very high wood removal values throughout the obtained working interval of the sanding means: 400 min for alder and 480 min for beech. After the first 20 min of a very sharp decline of the wood removal (the initial sharpness phase), the phase of the work sharpness with a balanced value of the wood removal follows. When sanding the beech wood, the sanding belt would be able to work even after 480 min, because its wood removal value has not fallen below the specified value of ≤0.05 g·cm^{-2}·min^{-1}. When sanding oak wood, from the perspective of the minimal wood removal criterion, the operational life of the sanding means is shorter (compared to the working time of 480 min), about 280–300 min, with the value of the wood removal decreasing to zero, which corresponds to the dulling phase of the sanding means. For pine wood, the working time of the sanding means reached only 160 min, which could be caused by a very high value of wood removal in the initial phase, in combination with the presence of a resin in the pine wood.

4.4. Sanding in a Perpendicular Direction to the Wood Fibres

The shortest sanding means working interval of 140 min was obtained when sanding the alder wood, where enormous wood removal values were observed in the initial phase of sharpness, which probably filled the space between the grains; with the further activity of the belt, the working conditions became more difficult until the belt broke [18,20]. Again, the beech wood proved to be a well-sanded wood, with a high wood removal value and a working time of 460 min. For oak and pine wood, similar wear curves were obtained, with a minimum wood removal value in the sharpness phase of the work, which, after about 240 min, was only about $\leq$0.09 g·cm^{-2}·min^{-1}. The working times of the sanding means were 480 min for pine wood and 380 min for oak wood.

4.5. Total Wood Removal

Efficiency of the sanding means is defined by the overall wood removal volume (in grams for the carried-out experiment). Although sharp sanding belts have been used for all variants in the experiment, with the same input characteristics and from the same manufacturer, the overall wood removal values were very different (beech and oak). The total wood removal value for beech wood was approximately twice as high as for oak wood (for example, for the sanding direction 60°; Figure 7). Thus, in terms of overall performance, the wood that must be sanded plays a significant role [34]. This is in agreement with the results of [36], who emphasized that, for the optimum performance of the sanding belt, the various sanding parameters should be considered as a function of the wood species [27].

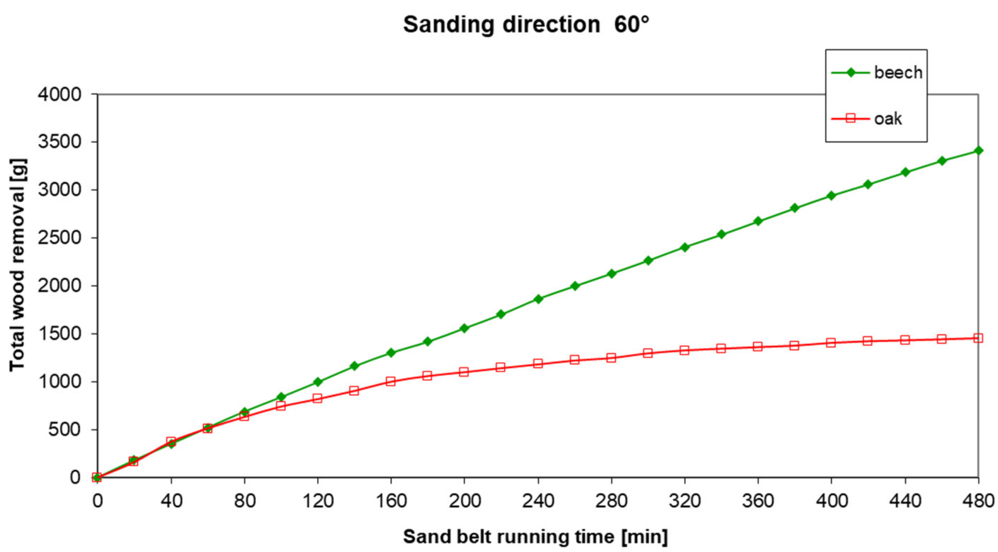

Figure 7. Total wood removal of the sanding means for beech and oak, sanding direction of 60° to the wood fibres.

Although these results were obtained from laboratory experiments and do not completely copy the practice, they indicate the high importance of such an analysis.

Tool wear is most often assessed at two levels, from the point of view of the criterion of optimal dulling of the tool or from the point of view of the technological criterion, which is the quality of the obtained surface. In the presented article, we used the criterion for the blunting of the sanding belt stated by the value of specific wood removal. In our opinion, only specific wood removal has significant informative value, as it affects all aspects of wear of the sanding belt (wear of the cutting edges of the grains, loss of the sanding grains, and clogging of the sanding belt). Even in real practice, the individual decides to change the sanding belt when it stops sanding and does not remove material.

The evaluation of our experiments is in terms of specific wood removal and in terms of the working time (life) of the individual sanding belt for the set boundary conditions.

Set boundary conditions:

- Appears to be the most suitable for beech wood, both in terms of specific wood removal value and its balanced value within the whole phase of the working sharpness of the sanding belt, but also the working time or durability (the life) of the sanding belt;
- Less suitable for oak, where the specific wood removal value decreases to a minimum within the working sharpness phase, and thus the sanding belt wear occurs earlier than the working time of the sanding belt;
- For alder and pine woods, the set boundary conditions are unsatisfactory, especially in terms of the working time of the sanding belts, when the sanding belt would have to be replaced several times within the monitored interval.

On the basis of these experiments, it can be clearly confirmed, from the perspective of the sustainable manufacturing process, that:

- Different woods sand differently in terms of efficiency—the wood removal value—but also in terms of the working time of the sanding means. An important role here is played by the macroscopic structure of wood, the physical (especially density) and mechanical properties of wood and their anisotropy, the chemical composition (content of extractives, e.g., high in oak, or resin in coniferous wood), and the microscopic and sub-microscopic structure (proportion of thick-walled fibrous elements, e.g., oak) of the wood;
- The pressure of the sanding means on the surface of the workpiece is to be assessed in terms of the type of sanded wood, the direction of sanding, the final technology for which the sanding is implemented (because it significantly affects the immediate efficiency of the sanding means), the maximum capacity of the sanding means, the wear itself (durability), and the service life of the sanding means;
- Short-term experiments that copy only the first phase of the wear of the sanding means—the phase of the initial sharpness—do not give unambiguous answers to the suitability of the input factors adjustment. Different pressure values suited the work of the sanding means in the initial sharpness phase, but did not satisfy in the phase of working sharpness, and the belts were either disrupted from overload or their efficiency was not used to the maximum, as evidenced by long-term experiments (selected work time: 480 min);
- Selecting one type of sanding means (spreading) for all wood types is not appropriate since soft wood with scattered pores has a high wood removal value in the initial sharpness phase, but quickly fills the space between the grains, and the load of the sanding means increases rapidly and the sanding means are disrupted. Certainly, it would be appropriate to select a belt with another form of a spreading, e.g., with open or semi-opened spreading, since the greater the gaps among the abrasive grains, the greater the space for chip removal, so that the chip does not crumble and does not significantly clog the spaces between the abrasive grains, compared to the dense spreading;
- For the sanding of coniferous wood containing resin, it is necessary to use belts with an antistatic treatment, but also belts with another form of spreading, since the fibrous cellular elements of coniferous trees, contrary to deciduous trees, are longer, and thus the particles are engraved in the surface of the wood, especially when sanding along the fibres is longer and, in combination with resin, quickly fills the space between the grains, reducing the ability to remove the chips and rapidly increasing the load on the sanding means, resulting in the replacement of the belt from the operation;
- We prefer the selection of quality sanding means, despite higher input costs, but with a higher immediate efficiency and maximum capacity of the sanding means, and, in particular, with a higher durability, or operational life, of the sanding means.

5. Conclusions

The results of the presented article answer two important levels of experimentation. The first level concerns the optimization of the pressure of the sanding belt on the surface of the sample to prolong its life. The value of 1.04 N·cm^{-2} seems to be the most suitable for our other boundary conditions.

The second level presents the results of the wear of the sanding belt with the selected optimal pressure and the boundary conditions, which appear to be the most suitable for beech and the least suitable for alder and pine.

These results point to variability within different materials with specific properties (especially wood), such as different anatomical structures, different chemical compositions of the wood, and variability of the cutting models, which must be thoroughly evaluated within each operation.

In practice, everyone knows what wood is the most frequently processed in his/her operation, and it is necessary to make preliminary measurements because it can also significantly affect the efficiency of the sanding means, or their durability, but also their operational life and, thus, the time when the sanding belt should be removed from the operation.

In terms of a sustainable manufacturing process within the context of wood sanding, this contribution points to one pillar—waste management—where the metrics are savings of materials, waste minimization, number of consumables discarded, and what the authors have materialized by extending the operating life of the sanding belts via the appropriate choice of input factor settings. It can also be concluded that another pillar of the sustainable manufacturing process was also affected—energy consumption—which is also related to the production costs themselves.

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References

1. Nemec, L'.; Šulán, E.; Zemiar, J. *Technológia Výroby Nábytku*; 1. Vydanie; Alfa: Bratislava, Slovakia, 1985.
2. Očkajová, A. *Analýza Faktorov v Procese Plošného Brúsenia Dreva*; Technická Univerzita vo Zvolene: Zvolen, Slovakia, 2002; ISBN 978-80-228-1185-8.
3. Siklienka, M.; Kminiak, R.; Šustek, J.; Jankech, A. *Delenie a Obrábanie Dreva*; Technická Univerzita vo Zvolene: Zvolen, Slovakia, 2017; ISBN 978-80-228-2845-1.
4. Pahlitzsch, G. Internationaler Stand der Forschung auf dem Gebiet des Schleifens von Holz. *Holz Als Roh Werkst.* **1970**, *28*, 329–343. [CrossRef]
5. Kato, C.; Fukui, H. The cutting force and the stock removal rate of coated abrasives in sanding wood under constant sanding pressure. *J. Jpn. Wood Res. Soc.* **1976**, *22*, 349–356.
6. Stewart, H.A. Abrasive planning across the grain with higher gruit numbers can reduce finish sanding. *For. Prod. J.* **1976**, *26*, 49–51.

7. Taylor, J.B.; Carrano, A.L.; Lemaster, R.L. Experimental Modeling of the Sanding Process: The Relationship between Input and Output Parameters. In Proceedings of the 14th International Wood Machining Seminar, Paris, Epinal, Cluny, France, 12–19 September 1999; pp. 73–82.
8. Matsumoto, H.A.; Murase, Y. The Effects of Sanding Pressure and Grit Size on Both AE and Sanding Performace in Disc Sanding Process. In Proceedings of the 14th International Wood Machining Seminar, Paris, Epinal, Cluny, France, 12–19 September 1999; pp. 653–662.
9. Očkajová, A.; Siklienka, M.; Barcík, Š. Physico-mechanical phenomenons in sanding process of natural and modified wood. In Proceedings of the 14th International Wood Machining Seminar Paris, Epinal, Cluny, France, 12–19 September 1999; Volume 2, pp. 691–700.
10. Saloni, D.E.; Lemaster, R.L.; Jackson, S.D. Abrasive machining process characterization on material removal rate, final surface texture, and power consumption for wood. *For. Prod. J.* **2005**, *55*, 35–41.
11. Saloni, D.E.; Lemaster, R.L.; Jackson, S.D. Process Monitoring Evaluation and Implementation for the Wood Abrasive Machining Process. *Sensors* **2010**, *10*, 10401–10412. [CrossRef] [PubMed]
12. Potkány, M.; Gejdoš, M.; Debnár, M. Sustainable Innovation Approach for Wood Quality Evaluation in Green Business. *Sustainability* **2018**, *10*, 2984. [CrossRef]
13. Marková, I.; Jaďuďová, J.; Hroncová, E. Assessment the Region's Sustainability through Quality Labels for Small Farmers' Products. *Slovak Case Study* **2018**. [CrossRef]
14. A/RES/70/1 Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://stg-wedocs.unep.org/bitstream/handle/20.500.11822/11125/unepswiosm1inf7sdg.pdf?sequence=1 (accessed on 25 September 2015).
15. *World Commission on Environment and Development Our Common Future*; Oxford University Press: Oxford, NY, USA, 1987; ISBN 978-0-19-282080-8.
16. Haapala, K.R.; Zhao, F.; Camelio, J.; Sutherland, J.W.; Skerlos, S.J.; Dornfeld, D.A.; Jawahir, I.S.; Clarens, A.F.; Rickli, J.L. A Review of Engineering Research in Sustainable Manufacturing. *J. Manuf. Sci. Eng.* **2013**, *135*, 041013. [CrossRef]
17. Lu, T.; Gupta, A.; Jayal, A.D.; Badurdeen, F.; Feng, S.C.; Dillon, O.W., Jr.; Jawahir, I.S. A Framework of Product and Process Metrics for Sustainable Manufacturing. In *Proceedings of the Advances in Sustainable Manufacturing*; Seliger, G., Khraisheh, M.M.K., Jawahir, I.S., Eds.; Springer: Berlin, Germany, 2011; pp. 333–338.
18. Ratnasingam, J.; Reid, H.F.; Perkins, M.C. The productivity imperatives in coated abrasives—Application in furniture manufacturing. *Holz Als Roh Werkst.* **1999**, *57*, 117–120. [CrossRef]
19. Saloni, D.E.; Lemaster, R.L.; Jackson, S.D. Control system evaluation and implementation for the abrasive machining process on wood. *BioResources* **2011**, *6*, 2763–2775. [CrossRef]
20. Ratnasingam, J.; Reid, H.F.; Perkins, M.C. The abrasive sanding of Rubberwood (Hevea brasiliensis): An industrial perspective. *Holz Als Roh Werkst.* **2002**, *60*, 191–196. [CrossRef]
21. Siklienka, M.; Očkajová, A. The study of selected parameters in wood sanding in the dependence on sanding pressure. In *Proceedings of the 15th International Wood Machining Seminar*; Wood Machining Institute: Berkeley, CA, USA, 2001; pp. 485–490.
22. Požgaj, A.; Chovanec, D.; Kurjatko, S.; Babiak, M. *Štruktúra a Vlastnosti Dreva*; 2. vyd.; Bratislava: Príroda, Slovakia, 1997; ISBN 80-07-00960-4.
23. Čunderlík, I. *Štruktúra Dreva*; Technická univerzita vo Zvolene: Zvolen, Slovakia, 2009; ISBN 978-80-228-2061-5.
24. Ratnasingam, J.; Scholz, F. *Wood Sanding Processes an Optimization Perspective*; Colorcom Grafik Sistem: Kuala Lumpur, Malaysia, 2004; ISBN 978-983-2446-84-2.
25. Pędzik, M.; Stuper-Szablewska, K.; Sydor, M.; Rogoziński, T. Influence of Grit Size and Wood Species on the Granularity of Dust Particles during Sanding. *Appl. Sci.* **2020**, *10*, 8165. [CrossRef]
26. Rogozinski, T.; Dolny, S. Influence of moisture content on the apparent densities of dust from sanding of alder wood. In *Proceedings of the Trieskové a Beztrieskové Obrábanie Dreva '04*; Zborník Prednášok z MVK: Starý Smokovec–Tatry, Slovakia, 2004; pp. 205–208.
27. Očkajová, A.; Kučerka, M.; Krišťák, Ľ.; Ružiak, I.; Gaff, M. Efficiency of sanding belts for beech and oak sanding. *BioResources* **2016**, *11*, 5242–5254. [CrossRef]
28. Buda, J.; Souček, J.; Vasilko, K. *Teória Obrábania*; 2. vyd.; Alfa: Bratislava, Bratislava; SNTL: Praha, Czech Republic, 1988.
29. Sydor, M.; Mirski, R.; Stuper-Szablewska, K.; Rogoziński, T. Efficiency of Machine Sanding of Wood. *Appl. Sci.* **2021**, *11*, 2860. [CrossRef]
30. Očkajová, A.; Siklienka, M. The influence of chosen factors of wood sanding upon the efficiency of sand belt. *Drevársky Výskum* **2000**, *45*, 33–38.
31. Očkajová, A. Sand belt running time and its wear. *Acta Fac. Xylologiae* **1999**, *XXXXI*, 9–13.
32. Miao, T.; Li, L. Study on influencing factors of sanding efficiency of abrasive belts in wood materials sanding. *Wood Res.* **2014**, *59*, 835–842.
33. Pahlitzsch, G. Vergleichende Untersuchungen der Schleiffähigkeit und Wirtschafklichkeit von Schleifpapieren. *Mettalloberfläche* **1952**, *6*, 53–61.
34. Očkajová, A.; Siklienka, M.; Barcík, Š. *Sand Belt Wear in the Dependence on Sanding Direction for Beech, Alder, oak and Pine Samples*; Faculty of science and engineering, Shimane University: Matsue, Japan, 2003; pp. 539–545.

35. Siklienka, M.; Naščák, Ľ.; Banski, A. Monitorovacie zariadenie pre sledovanie kontaktných javov pri brúsení dreva. *Zborník Ref. Stroj-Nástroj-Obrobok* **1999**, *57*, 117–121.
36. Porankiewicz, B.; Banski, A.; Wieloch, G. Specific resistance and specific intensity of belt sanding of wood. *BioResources* **2010**, *5*, 1626–1660.